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Optical and infrared interferometry

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Abstract. Interferometric techniques are at the forefront of modern astronomical instrumentation. A new generation of instruments are either operating or nearing completion, including arrays of small telescopes as well as the “big guns” (VLTI and Keck). A number of space interferometers for the detection of extra-solar planets are also being planned. I will review the current state of play and describe the latest developments in the field.

1. Introduction

It is somewhat disappointing that a meeting on “Galaxies and their Constituents at the Highest Angular Resolutions” contains so few results from optical interferometry¹. To some extent, this reflects the interests of those on the Scientific Organising Committee, but it must also be taken as a sign that optical interferometry has yet to deliver on its promises. Why is this? One reason is surely the difficulty of the technology and its vulnerability to Hofstadter’s Law (1980):

Hofstadter’s Law — It always takes longer than you expect, even when you take into account Hofstadter’s Law.

But progress is being made, and there is a large number of interferometry projects in various stages of development and operation. The following is the current list of operating interferometers, listed in the order in which they obtained first fringes:

- GI2T/REGAIN (Grand Interféromètre à 2 Télescopes).
- SUSI (Sydney University Stellar Interferometer)
- COAST (Cambridge Optical Aperture Synthesis Telescope)
- ISI (Infrared Spatial Interferometer)
- FLUOR (Fiber Linked Unit for Optical Recombination)
- IOTA (Infrared-Optical Telescope Array)
- NPOI (Navy Prototype Optical Interferometer)
- PTI (Palomar Testbed Interferometer)

¹In this review, the term “optical” is also meant to include infrared wavelengths.

- CHARA (Center for High Angular Resolution Astronomy)

The following are under construction (in alphabetical order, since I am not game to predict which will be first to get fringes!):

- Keck Interferometer
- LBT (Large Binocular Telescope)
- MIRA-II (Mitaka IR Array)
- VLTI (Very Large Telescope Interferometer)

Finally, there are planned space missions, including SIM, TPF and DARWIN.

More details of all these projects can be found via links from the Web-based “Optical Long Baseline Interferometry News,” currently maintained by Peter Lawson². Here, I simply want to stress the number and range of the projects, and to point out that many of them are producing scientific results. The proceedings of recent conferences (Unwin & Stachnik 1999; Lena & Quirrenbach 2000) testify to the vigorous activity in this field. In Section 3., I highlight some areas in which recent technological developments have been made. First, however, it is appropriate to make some general remarks about optical interferometry.

2. Interferometers measure fringes!

Realising that interferometers measure fringes is the key to understanding their capabilities and limitations (see, e.g., Bedding 1997; Quirrenbach 1997). To observe an object, an interferometer must be able to detect fringes and track them. This requires that the object has a sufficiently compact bright component, or that a suitable reference source (e.g., a star) is located nearby on the sky.

The main observable is the fringe contrast – the visibility – which is a dimensionless number between zero and one that indicates the extent to which a source is resolved on the baseline being used. Importantly, the signal-to-noise with which the visibility can be measured is a function of NV^2 , where N is the number of photons detected per sub-aperture per integration time, and V is the *measured* visibility (including the inevitable reduction by atmospheric and instrumental effects). This dependence on NV^2 implies that interferometry becomes increasingly difficult for faint sources, but also for those with complex structures. For example, a drop in visibility from 1 to 0.1 as a source becomes resolved is equivalent, in terms of signal-to-noise, to a drop in brightness by a factor of 100 (5 magnitudes)!

The NV^2 limit can be addressed in several ways:

- Using larger sub-apertures. However, this requires adaptive optics if the telescope diameter becomes much larger than r_0 , the average scale over which the wavefront is flat.
- Bootstrapping to increase integration times, which can be achieved by tracking fringes over a connected series of short baselines to allow low-visibility fringes to be measured on the longest. This approach requires

²<http://huey.jpl.nasa.gov/olbin/>

lots of telescopes, which must be deployed rather wastefully in terms of (u, v) coverage.

- Tracking fringes on a point source to increase integration time on the target. This is best done with a dual-feed system.

3. Recent developments

3.1. Fibres and integrated optics

Single-mode optical fibres have been used very successfully for spatially filtering light beams (Coude Du Foresto et al. 1997). This allows visibility amplitudes to be measured to high precision (about one percent), by reducing the sensitivity to atmospheric fluctuations. So far, results have been demonstrated with IOTA in the K band (2.2 micron; Perrin et al. 1999) and now in the L band (3.75 micron; Mennesson et al. 1999). It seems clear that fibres have an important role to play in interferometry, especially in the infrared.

A related development is in the field of integrated optics, which potentially allows large tables of bulk optics to be replaced by miniature devices. White-light interference has been achieved in the laboratory with two (Berger et al. 1999) and three beams (Haguenauer et al. 2000). It is too soon to estimate the impact of this technology on optical interferometers, with applications in space perhaps being the most likely.

3.2. Mid-infrared interferometry

The only interferometer operating in the mid-infrared is the ISI, which has a heterodyne system. A recent development has been the application of ISI to spectral-line observations of molecules around giant stars (Monnier et al. 2000). Both VLTI and Keck are targeting the mid-infrared, which is very attractive because the 8–10-m apertures are essentially diffraction-limited at 10–20 microns. A lot of excellent science can be expected from those instruments, provided the problems with thermal background can be overcome, but the amount of observing time will obviously be limited.

3.3. Imaging

Imaging is often seen as the main goal of interferometry, despite the fact that a lot of scientific questions can be answered without reconstructing an image. We must not expect high-quality VLA-type images from optical interferometers, given the much smaller number of array elements and the much larger atmospheric phase fluctuations. Instead, the correct parallel to draw is with VLBI, in which closure-phase imaging is a well-established technique. The first crude images from optical arrays have been produced for binary stars (Baldwin et al. 1996; Hummel et al. 1998) and barely-resolved single stars (Young et al. 2000).

The key to good imaging is a large number of array elements. This is well known by radio astronomers, and the potential in the optical is shown by the spectacular images produced with aperture-masking of single telescopes such as the Keck (Tuthill et al. 2000). Images from current long-baseline arrays will not be this good, since none has more than six elements. The next generation of imaging interferometers will need at least ten, and preferably fifteen elements.

3.4. Differential phase measurements

Apart from fringe visibility, the other main observable for an interferometer is fringe phase. With three or more telescopes, closure phases can be used to reconstruct complex objects, as mentioned above. But even with two telescopes, useful phase measurements can be made. These involve measuring the differential phase of one object relative to another (or one object relative to itself at different wavelengths), which allows very precise astrometry. A nice feature of differential phase measurements is that much interesting science can be done with point sources (i.e., stars), so that the NV^2 limitation is overcome. Examples include parallaxes and proper motions, such as small motions induced by the gravitational pull of unseen planets and, for dual-wavelength observations, the shift in photo-centre caused by the presence of a “hot Jupiter” planet.

The key technological element is a dual feed, in which two stars are observed simultaneously so that their differential phase can be measured. Such a system also allows dual-wavelength operation, in which a single star is observed at two wavelengths with the two feeds. Finally, the second feed can instead be used for fringe tracking on a reference star, giving longer integration times on a fainter and/or more complex source. All these techniques have been demonstrated for the first time with the PTI (Lane et al. 2000) and, although problems remain, it appears that plans to apply these techniques to the Keck Interferometer and space missions are feasible.

3.5. Nulling

Methods for using an interferometric null to allow a faint object (e.g., a planet) to be seen next to a bright star are being developed by many groups (Hinz et al. 1998; Guyon et al. 1999; Böker & Allen 1999; Velusamy et al. 1999; Ollivier et al. 2000; Wallace et al. 2000). Deep and stable nulls have now been demonstrated in the laboratory and with telescopes, and nulling capabilities will be included in the Keck Interferometer. The scientific aims include direct detection of exoplanets, and also of exo-zodiacal dust. Eventually, it is hoped that space interferometers will provide images and even spectra of Earth-like exoplanets. And that somewhat optimistic – but perhaps achievable – scenario seems a good place to end this review!

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